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Top-Quark Production and Decay in the MSSM[1]

J. Guasch[a], W. Hollik[a], J.I. Illana[b,c], C. Schappacher[a], J. Solà[d]

[a] *Institut für Theoretische Physik, Universität Karlsruhe, D-76128 Karlsruhe, Germany*
[b] *DESY, Platanenallee 6, D-15738 Zeuthen, Germany*
[c] *Dpto. Física Teórica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain*
[d] *Grup de Física Teòrica and Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, E-08193 Bellaterra (Barcelona), Catalonia, Spain*

Abstract

We review the features of top-quark decays and loop-induced effects in the production cross section and CP-violating observables of $e^+e^- \to t\bar{t}$ which are specific to the R-parity conserving Minimal Supersymmetric Standard Model (MSSM).

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1 Introduction

The Standard Model (SM) of strong (QCD) and electroweak (EW) interactions has been the most successful framework to describe the phenomenology of high energy physics. However, one of the fundamental building blocks (the Higgs boson) still lacks experimental confirmation. On the other hand, the SM still suffers from some theoretical deficiencies, most notably the hierarchy problem. Several extensions of the SM have been proposed to solve these problems; in this note we will concentrate on its supersymmetric (SUSY) extension, more specifically to the R-parity conserving Minimal Supersymmetric Standard Model (MSSM) [1].

The top quark, due to its large mass, could play a central role in the search of physics beyond the SM. On one hand it could decay to non-standard particles, on the other hand, due to its large Yukawa coupling, the effects of the Spontaneous Symmetry Breaking Sector are expected to be larger than for any other particle of the model. In the MSSM, these effects are reinforced by the presence of the SUSY partners of the top quark and Higgs bosons. Moreover, the new parameters appearing in the MSSM can have complex phases, and new sources of CP-violation phenomena can appear.

One should also bear in mind that, before the commissioning of TESLA, the LHC will be producing data which might turn out to include some physics beyond the SM, and we must be prepared for whatever the high energy physics scenario would be for the running of TESLA.

Here we present a review of the effects of SUSY in the top-quark phenomenology. First we review in section 2 the top-quark decay within the framework of the MSSM; then, in section 3, we present the MSSM effects on the top quark pair production in e^+e^- collisions, both in the presence and absence of CP-violating couplings.

2 Top-quark decays

The existence of SUSY could affect the total top-quark decay width in two ways. First of all through unexpected radiative corrections to the standard top quark decay process $t \to W^+ b$. Second, some of the SUSY particles could be lighter than the top quark itself, thus providing new channels in which the top quark could decay.

Concerning the standard top-quark decay, we point out that its branching ratio BR$(t \to W^+ b)$ is not so severely constrained by the observed top quark production cross section as one could naively think at first sight [2]. In the MSSM the total observed cross section can be written, schematically, as

$$\begin{aligned} \sigma_{\rm obs} &= \int dq\, d\bar{q}\; \sigma(q\,\bar{q} \to t\,\bar{t}) \;\times |{\rm BR}(t \to W^+\, b)|^2 \\ &+ \int dq\, d\bar{q}\; \sigma(q\,\bar{q} \to \tilde{g}\,\bar{\tilde{g}}) \;\times |{\rm BR}(\tilde{g} \to t\,\bar{\tilde{t}}_1)|^2 \times |{\rm BR}(t \to W^+\, b)|^2 \\ &+ \int dq\, d\bar{q}\; \sigma(q\,\bar{q} \to \tilde{b}_a\,\bar{\tilde{b}}_a) \;\times |{\rm BR}(\tilde{b}_a \to t\,\chi_1^-)|^2 \times |{\rm BR}(t \to W^+\, b)|^2 + \ldots \end{aligned} \quad (1)$$

Here $\int dq$ represents the integration over the quarks Parton Distribution Functions, and sumation over quark flavours. In the SM only the first line of this equation is present. It follows that, in the MSSM, our present ignorance of the SUSY parameters prevents us from performing a detailed calculation of the $t\bar{t}$ production cross section as well as from putting a strict limit on BR($t \to$"new") — the branching ratio of the top quark into new physics. It should also be clear that the observed cross section in Eqn. (1) refers not only to the standard $bW\,bW$ events, but to all kind of final states that can mimic them. Thus, effectively, we should substitute BR($t \to X\,b$) in that formula for BR($t \to W^+\,b$), and then sum the cross section over X, where X is any state that leads to an observed pattern of leptons and jets similar to those resulting from W-decay. In particular, $X = H^\pm$ would contribute (see below) to the τ-lepton signature, if $\tan\beta$ is large enough. Similarly, there can be direct top quark decays into SUSY particles that could mimic the SM decay of the top quark [3]. The only restriction is an approximate lower bound BR($t \to W^+\,b$) $\gtrsim 40 - 50\%$ in order to guarantee the purported standard top quark events at the Tevatron [4]. Thus, from these considerations it is not excluded that the non-SM branching ratio of the top quark, BR($t \to$"new"), could be comparable to the SM one — or at least not necessarily much smaller.

The e^+e^- Linear Collider (LC) provides an excellent tool to test the various top quark partial decays widths. The total top quark decay width can be measured by means of a threshold scan, in a model independent way [5]. Also the clean environment allows for a high prospect for detecting exclusive rare decay channels.

2.1 The top-quark standard decay width

In the SM the top-quark decays into a W^+ gauge boson and a bottom quark. The tree-level prediction for this partial decay width is (for $m_t = 175\,GeV$)

$$\begin{aligned}\Gamma^0_{\rm SM}(t \to W^+ b) &= \left(\frac{G_F}{8\pi\sqrt{2}}\right)\frac{|V_{tb}|^2}{m_t}\lambda^{1/2}(1, m_b^2/m_t^2, M_W^2/m_t^2) \\ &\quad\times[M_W^2(m_t^2+m_b^2)+(m_t^2-m_b^2)^2-2M_W^4] \simeq 1.55 \text{ GeV} \qquad (2)\end{aligned}$$

where $\lambda^{1/2}(1, x^2, y^2)$ is the usual Källen function. As the width turns out to be much larger than the typical scale of non-perturbative QCD effects Λ_{QCD}, it can be conceived as an effective infrared cut-off. This means that the top quark, due to its large mass, has time to weakly decay before strong hadronization processes come into play. And for this reason perturbative computations in top quark physics are reliable.

In this spirit the SM quantum corrections to the standard top quark decay width have been performed. The short-distance QCD effects have been computed up to two-loop level [6, 7] and they amount to a correction of -10% with respect to the tree-level width. The electroweak (EW) SM radiative correction is also available [7,8], but this contribution is below $+2\%$ in a scheme where the tree-level width is parametrized in terms of the Fermi constant G_F — as in Eqn.(2). In this scheme the electroweak corrections are minimized both in the SM and in the MSSM because the set of universal contributions — viz. those encoded in the parameter Δr — cancel out.

The MSSM may furnish extra (perturbative) quantum effects on the standard decay width of the top quark through the one-loop corrections mediated by non-SM particles. They have been computed in [9, 10][2] and can be of two types, electroweak and strong.

[2]The corresponding corrections in the general 2HDM can be found in Refs. [11, 12]. The particularization of these Higgs effects in the MSSM is studied in [11].

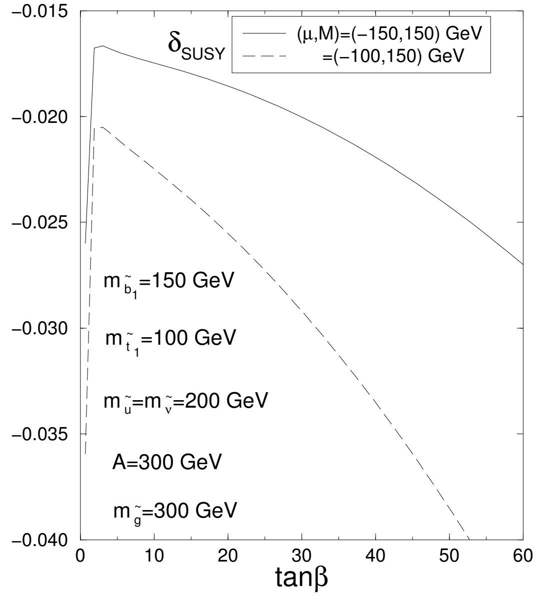


Figure 1: The total (electroweak and strong) SUSY correction to $\Gamma(t \to W^+ b)$ for given sets of parameters and $m_t = 175$ GeV.

The SUSY-EW quantum corrections [9] are negative (as the standard QCD ones) and vary from -1% to -10%, depending on the choice of the various SUSY parameters, and, especially of $\tan\beta$. The corrections due to additional Higgs particle exchange (i.e. the MSSM Higgs effects after subtracting the corresponding SM limit of the MSSM Higgs sector) are at most of 0.1% due to the severe constraints that SUSY imposes on the MSSM Higgs sector.

The SUSY-QCD corrections, mediated by gluinos and squarks, have also been found to be negative in most of the parameter space [10], though they are in general smaller than the SUSY-EW ones — namely, around a few % level — and they are independent of $\tan\beta$.

In Fig. 1 we show the total SUSY (electroweak and QCD) corrections to this decay width for typical values of the SUSY spectrum. The upshot is that the total SUSY corrections to $\Gamma(t \to W^+ b)$ go in the same direction as the standard QCD ones. For large values of $\tan\beta$ they can typically yield an effect about half the size of the QCD corrections, thus providing an additional (potentially measurable) decrease of the tree-level value of the standard width (2).

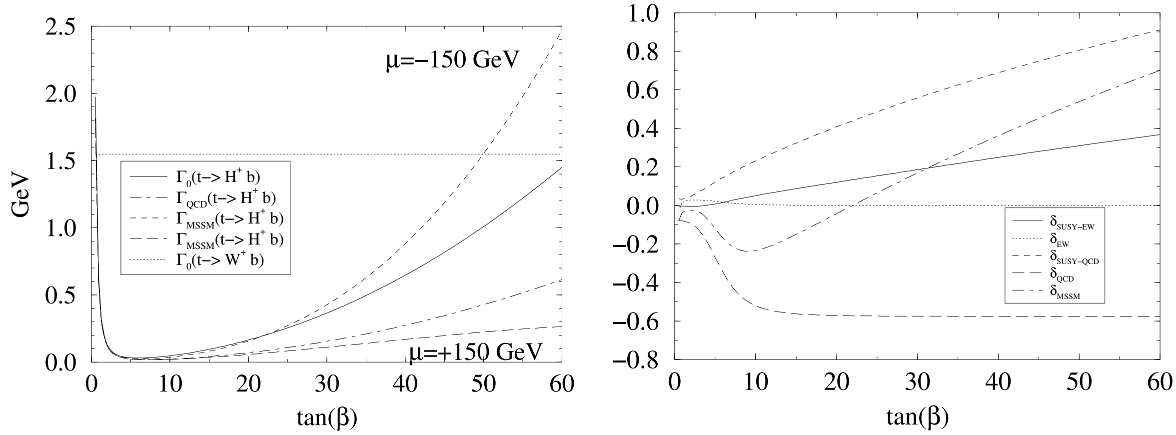
2.2 Top-quark decay into charged Higgs

If the charged Higgs is light enough the top quark will also decay through the process $t \to H^+ b$. This decay has been subject of interest since very early in the literature [13]. If $\tan\beta$ is large or small enough the tree-level prediction for the partial decay width $\Gamma^0(t \to H^+ b)$ is comparable to the standard one (2). In fact $\Gamma^0(t \to H^+ b)$ presents a minimum at the point $\tan\beta = \sqrt{m_t/m_b} \simeq 6$ and grows for larger or smaller values of $\tan\beta$ (see Fig. 2). Remarkably enough, this process turns out to be extremely sensitive to radiative corrections of all kinds. On one hand, the standard QCD corrections are quite large. They are negative and for $\tan\beta \gtrsim 10$ they saturate around the value -58% [14]. On the other hand, the full set of the MSSM radiative corrections, at the one-loop level, can also be very important. They have been computed in [15–17], and more recently the general 2HDM corrections became also available [18].

In the case of the EW corrections one needs to define renormalization prescriptions also for the non-SM parameters that appear in these decays, in particular for the highly relevant parameter $\tan\beta$. The renormalization counterterm for $\tan\beta$ can be fixed in many different ways. The actual corrections will depend on the particular definition, but not so the value of the physical observable, of course. In our case we found it practical to define $\tan\beta$ through the condition that the partial decay width $\Gamma(H^+ \to \tau^+\nu_\tau)$ does not receive radiative corrections. This is a good choice for the scenario under study, since this is the dominant decay of a light charged Higgs boson (i.e. $M_{H^\pm} < m_t$) provided $\tan\beta$ is of order 1 or above: $\tan\beta > \sqrt{m_c/m_s} \gtrsim 2$. Under this renormalization prescription, and for moderate or large $\tan\beta \gtrsim 10$, the bulk of the SUSY quantum corrections are known to stem from the finite threshold corrections to the bottom mass counterterm. The relevant effects are triggered by R-odd particles entering the bottom self-energy, and can be cast as follows [16, 17]

$$
\begin{aligned}
\left(\frac{\delta m_b}{m_b}\right)_{\rm S-QCD} &= \frac{2\alpha_s(m_t)}{3\pi}\, m_{\tilde g}\, M^b_{LR}\, I(m_{\tilde b_1}, m_{\tilde b_2}, m_{\tilde g}) \\
&\to -\frac{2\alpha_s(m_t)}{3\pi}\, m_{\tilde g}\, \mu \tan\beta\, I(m_{\tilde b_1}, m_{\tilde b_2}, m_{\tilde g})\,, \\
\left(\frac{\delta m_b}{m_b}\right)_{\rm S-EW} &= -\frac{h_t\, h_b}{16\pi^2}\,\frac{\mu}{m_b}\, m_t\, M^t_{LR} I(m_{\tilde t_1}, m_{\tilde t_2}, \mu) \\
&\to -\frac{h_t^2}{16\pi^2}\, \mu\, A_t \tan\beta\, I(m_{\tilde t_1}, m_{\tilde t_2}, \mu)\,, \\
I(m_1, m_2, m_3) &\equiv 16\,\pi^2 i\, C_0(0,0,m_1,m_2,m_3) \\
&= \frac{m_1^2\, m_2^2 \ln\dfrac{m_1^2}{m_2^2} + m_2^2\, m_3^2 \ln\dfrac{m_2^2}{m_3^2} + m_1^2\, m_3^2 \ln\dfrac{m_3^2}{m_1^2}}{(m_1^2-m_2^2)\,(m_2^2-m_3^2)\,(m_1^2-m_3^2)}\,,
\end{aligned} \tag{3}
$$

where C_0 is the three-point 't Hooft-Passarino-Veltman function [19], and the rightmost expressions hold for sufficiently large $\tan\beta$. Several important consequences can be derived already from the approximate expressions (3). The first one corresponds to the sign of the corrections. The sign of the SUSY-QCD corrections is opposite to that of the higgsino mass parameter μ, whereas the sign of the SUSY-EW corrections is given by the product of μ and the soft-SUSY-breaking trilinear coupling A_t. Second, both kind of corrections grow linearly with $\tan\beta$. A third, and important, observation is that, if we scale all the dimensionful parameters of Eqn. (3) by a factor λ, the λ-dependence drops out in the final expression. This means that raising the scale of SUSY breaking does not reduce the effects of the radiative corrections. Notice, however, that this consideration amounts to scale up also the trilinear coupling A_t as well as the higgsino parameter μ. Therefore, it may lead to unwanted fine-tuning effects in at least two important sectors



(a) (b)

Figure 2: **(a)** The top-quark partial decay width $\Gamma(t \to H^+b)$ compared with the standard one as a function of $\tan\beta$, and for $M_{H^\pm} = 120$ GeV. Shown are the tree-level width, the QCD corrected width, and the full MSSM corrected width for two sets of the SUSY parameters A: $\{\mu, m_{\tilde{t}_1}, m_{\tilde{b}_1}, m_{\tilde{g}}, A_t\}= \{-150, 100, 150, 300, +300\}$ GeV B:$\{+150, 200, 600, 1000, -300\}$ GeV. **(b)** The relative radiative corrections to $\Gamma(t \to H^+b)$ for each of the sectors of the MSSM (A parameter set).

of the MSSM: in the Higgs and squark sectors. Notwithstanding, if one does not stretch out the ranges of the parameters up to unreasonable limits (i.e. much beyond 1 TeV or so), an important consequence can be derived without disrupting the natural structure of the model, to wit: that the R-odd particles whose masses are above the EW scale can effectively display, in the presence of Yukawa couplings, a non-decoupling behaviour. And this behaviour is triggered by the existence of explicit soft SUSY-breaking terms in combination with the spontaneous breaking of the gauge symmetry. Obviously, this is a very important feature as it could produce visible radiative corrections for this decay.[3] Recently these finite threshold effects have been further refined in the literature and they have been re-summed to all orders [21].

In the case of the gluino mass dependence there is another trait that we wish to remark. Even without scaling up the rest of the SUSY parameters, the SUSY-QCD corrections to $\Gamma^0(t \to H^+b)$ exhibit a local, and lengthy sustained, maximum around $m_{\tilde{g}} \gtrsim 300$ GeV. Only for gluino masses well above the TeV scale (for fixed values of the squark masses) do these corrections eventually decouple [16]. As for the corrections due to Higgs bosons loops, of which there are quite a few, we find that they are entirely negligible compared to the yield from R-odd particles.[4]

Figure 2a presents a summary of the main results. Here we have plotted the partial decay width $\Gamma(t \to H^+b)$ as a function of $\tan\beta$, for the two different scenarios that have been identified. In the first one ($\mu < 0$) the SUSY-QCD corrections are opposite in sign to the QCD ones, thus canceling partially (or even totally) the SM strong corrections. In the

[3]We should like to say that this feature is not limited to just the high energy process under consideration, but it applies equally well to some low-energy processes, e.g. in B-meson decays [20].

[4]This effect is due to the restrictions that SUSY imposes to the form of the Higgs bosons potential. In the unrestricted 2HDM the Higgs bosons loop corrections can also be important [18].

second one ($\mu > 0$) the SUSY-QCD corrections have the same sign as the standard QCD ones, so reinforcing the large negative corrections. In both cases we have fixed $\mu A_t < 0$, which is the overall sign which makes allowance for the low energy data on radiative B meson decays to be compatible with the existence of a light charged Higgs below the top quark mass [22]. This fixes the SUSY-EW corrections (3) to be positive. In Fig. 2b we present the relative corrections induced by each sector of the MSSM, in the $\mu < 0$ scenario.

The results shown in Fig. 2 can hardly be overemphasized. Whereas the QCD prediction for the partial decay width states that this is always significantly smaller than the standard partial decay width, in the $\mu < 0$ scenario the charged Higgs partial decay width is equal to the standard one for $\tan\beta \simeq 50$, and it is rapidly increasing. In this scenario the presence of charged Higgs in top quark decays is significantly greater than the QCD prediction, and thus the experimental discovery reach of charged Higgs in top quark decays can be larger than expected. On the other hand in the $\mu > 0$ scenario the discovery reach is decreased with respect to the standard one. Thus the excluded region in the $\tan\beta - M_{H^\pm}$ plane due to the (up to now) unsuccessful search of charged Higgs bosons in top quark decays depends drastically on the value of the rest of parameters in the MSSM [23].

In Fig. 2b we see clearly the close-to-linear behaviour of the leading SUSY contributions (3), and we also see that the Higgs-boson mediated contributions (δ_{EW} in the plot) really play a marginal role. Interestingly enough we see that for $\tan\beta \simeq 35$ the SUSY-QCD corrections cancel the standard QCD ones, and thus, although the larger corrections are due to the strong interaction sector, the only radiative corrections that are left are the SUSY-EW ones.

The SUSY radiative corrections above $\tan\beta \simeq 35$ (at one-loop) can easily reach values of

$$\begin{aligned} &\delta_{\mathrm{S-EW}} \simeq +30\% \;, \;\; \delta_{\mathrm{S-QCD}} \simeq +80\% \;\; (\mu < 0, A_t > 0, M_{SUSY} \simeq 100 - 200 \text{ GeV}) \;, \\ &\delta_{\mathrm{S-EW}} \simeq +20\% \;, \;\; \delta_{\mathrm{S-QCD}} \simeq -40\% \;\; (\mu > 0, A_t < 0, M_{SUSY} \simeq 500 \text{ GeV}) \;. \end{aligned} \tag{4}$$

Negative corrections for the SUSY-EW corrections of the same absolute values are possible provided $\mu A_t > 0$. We have singled out different sparticle spectra for the two scenarios in order to avoid total corrections greater than 100% when they are added to the standard QCD corrections.

2.3 FCNC top-quark decays

Flavour Changing Neutral Current (FCNC) decays of the top quark are one-loop induced processes. They are such rare events in the SM [24], with branching ratios at the level of $10^{-10} - 10^{-15}$ depending on the particular channel, that its presence at detectable levels would clearly indicate the presence of new physics. The question is whether the presence of SUSY particles could enhance these partial decay widths up to the visible level. The partial FCNC decay width into a weak vector boson $\Gamma(t \to cV)$ $(V = Z\,, \gamma)$ undergoes some enhancement [25,26], however it is still of the order of $10^{-12} - 10^{-13}$ in most of the parameter space, thus being far away of the detection level. The gluon channel $(t \to cg)$ is the most gifted one in the SM, but it is nevertheless too small to be detectable ($\sim 10^{-10}$). This mode, however, has recently been analyzed in great detail in the MSSM [26–28] and one finds that its branching ratio can be close to the visible threshold for the future high luminosity machines such as the LHC and the LC (see below). Finally, the top quark decaying into neutral Higgs particles ($t \to ch$, $h = h^0$, H^0, A^0) has also been shown to benefit from large enhancements in the MSSM framework [29, 27, 28]. In this respect we recall that in the MSSM the channel in which the lightest Higgs boson is involved ($t \to ch^0$) is always kinematically open because $m_{h^0} \leq 130\, GeV < m_t$. Hereafter we will concentrate on the two decays, $t \to cg$ and $t \to ch^0$, because the overall analysis shows that they are the most efficient FCNC decays in their respective modalities. Of course in SUSY models beyond the MSSM, such as models without R-parity, there could be other kind of competing FCNC top quark decays,[5] but here we shall stick all the time to the MSSM.

FCNC processes can be induced through SUSY-EW charged current interactions. These proceed through the same mixing matrix elements as in the SM: the Cabibbo-Kobayashi-Maskawa mixing matrix. But in addition it could happen that the squark mass matrix squared is not proportional to the quark-mass-matrix squared. In this case the squark mass eigenstates would not coincide with the quark mass states, and as a consequence tree-level FCNC would appear in the quark-squark-gaugino/higgsino interactions. This mixing appears as non-flavour diagonal mass matrix elements in the squark mass matrix squared

$$(M^2_{LL})_{ij} = m^2_{ij} \equiv \delta_{ij}\, m_i\, m_j \ , \ (i \neq j) \ , \tag{5}$$

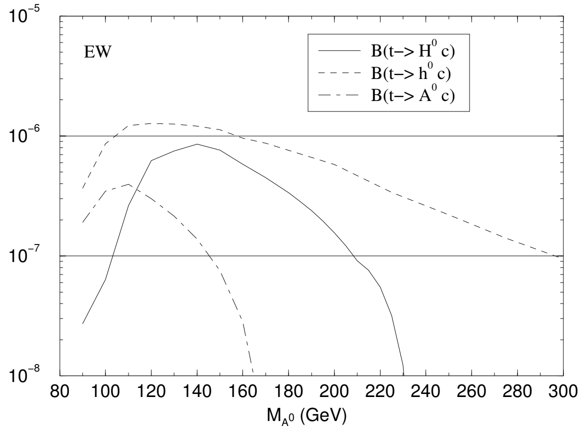
where i, j represent squarks of any generation, and $m_{\{i,j\}}$ is the mass corresponding to the diagonal entries in the matrix. In the MSSM these kind of mixing terms in the Left-chiral sector are naturally generated through the Renormalization Group evolution of the soft-SUSY-breaking squark masses down to the EW scale [31]. This is the reason why we just singled out the LL mixing component in Eqn. (5). Flavour mass mixing terms for the corresponding Right-chiral squarks are allowed, but they do not appear naturally in the GUT frameworks. Moreover its presence is not essential because it does not change the order of magnitude of the results obtained with only flavour-mixing between Left-chiral squarks [26, 27]. The mixing terms δ_{ij} are restricted by the low energy data on FCNC processes [32]. These limits were computed using the mass-insertion approximation, so they should be taken as order of magnitude limits. Recently it has been shown that the full computation of some FCNC process can give results which differ substantially from the mass-insertion approximation ones [33].

To assess the size of the FCNC top quark decay rates we use the fiducial ratio

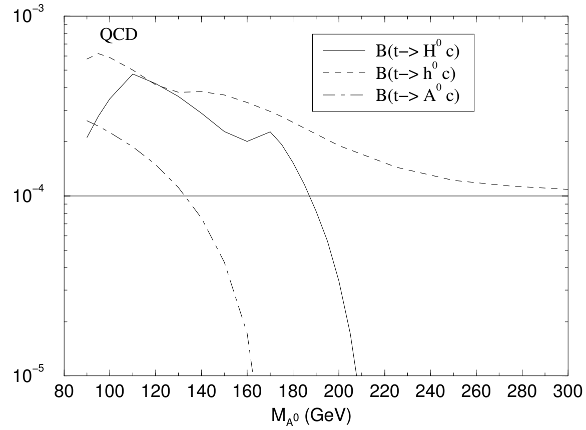
$$B(t \to c\, h) \equiv \frac{\Gamma(t \to c\, X)}{\Gamma(t \to b\, W^+)} \ , \tag{6}$$

for both $X = g, h^0$. The typical values of this ratio lie in the ballpark of 10^{-8} for the SUSY-EW contributions in the regime of large $\tan\beta$ ($30 \lesssim \tan\beta \lesssim 50$) and for a SUSY spectrum around 200 GeV. This is already five orders of magnitude larger than the corresponding processes in the SM. The SUSY-QCD contributions, which appear when

[5] See e.g. Refs. [30] for some recent works on the subject.



(a)



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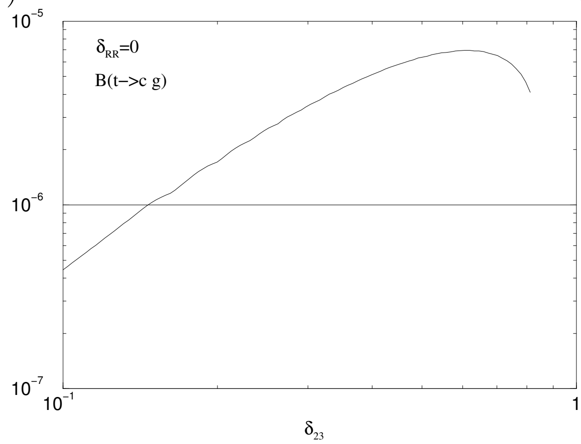

(c)

Figure 3: **(a)** Maximum value of $B(t \to c\,h)$, obtained by taking into account only the SUSY-EW contributions, as a function of M_{A^0} ; **(b)** as in (a) but taking into account only the SUSY-QCD contributions; and **(c)** maximum value of $B(t \to c\,g)$ as a function of the intergenerational mixing parameter δ_{23} in the LH sector. In all cases the scanning for the rest of parameters of the MSSM has been performed within the phenomenologically allowed region.

the δ_{23} in Eqn. (5) is non-zero for up-type squarks, are typically around two orders of magnitude larger, and they exhibit a slow decoupling as a function of the gluino mass, so even for gluinos as heavy as $m_{\tilde{g}} \simeq 500$ GeV the ratio $B(t \to ch^0)$ can reach the level of 10^{-5}. This large value is due to the strong nature of the gluino-mediated interactions, but not less to the fact that present bounds on δ_{23} are rather poor. Also the various decays are sensitive to both: the higgsino mass parameter μ and the soft-SUSY-breaking trilinear coupling A_t.

In Figs. 3a and b we present the result of maximizing the ratio (6) for the SUSY-EW and SUSY-QCD contributions respectively [27]. These plots have been obtained by performing a full scan of the MSSM parameter space, in the phenomenologically allowed region, and for SUSY parameters below 1 TeV. Needless to say, not all of the maxima can be simultaneously attained as they are obtained for different values of the parameters. Perhaps the most noticeable result is that the decay into the lightest MSSM Higgs boson

$(t \to c\,h^0)$ is the one that can be maximally enhanced, reaching values of order $B(t \to c\,h^0) \sim 10^{-4}$ that stay fairly stable all over the parameter space, and in particular for almost all the range of allowed Higgs boson masses in the MSSM.

For the sake of comparison, in Fig. 3 we show the maximized ratio for the competing decay $t \to cg$ as a function of the intergenerational mixing parameter between the second and the third generation, δ_{23} (5). We see that it never really reaches the critical value 10^{-5}, which can be considered as the visible threshold for the next generation of high luminosity colliders. To assess the discovery reach of the FCNC top quark decays for these future accelerators we take as a guide the estimations that have been made for gauge boson final states [34]. Assuming that all the FCNC decays $t \to c\,X$ $(X = V, h)$ can be treated similarly, we roughly estimate the following sensitivities for 100 fb^{-1} of integrated luminosity:

$$\textbf{LHC}: B \gtrsim 5 \times 10^{-5}\ ;\ \textbf{LC}: B \gtrsim 5 \times 10^{-4}\ ;\ \textbf{TEV33}: B \gtrsim 5 \times 10^{-3}\ . \tag{7}$$

Although the LHC seems to be the most sensitive machine to this kind of physics (due to its highest luminosity) the LC is also very competitive due to the cleanness of its environment which should allow a much more efficient isolation of the rare events. The upgraded Tevatron, unfortunately, looks not so promising in this respect.

To better assess the realistic possibilities for detecting the most serious FCNC top quark decay candidates, $t \to c\,h$ and $t \to c\,g$, we remark that around the loci of maximal rates in parameter space the following situation is achieved

$$5 \times 10^{-6} \lesssim B(t \to c\,g)_{\max} < B(t \to c\,h^0)_{\max} \lesssim 5 \times 10^{-4}. \tag{8}$$

In both types of decays the dominant effects come from SUSY-QCD. However, it should not be undervalued the fact that the maximum electroweak rates for $t \to c\,h$ can reach the 10^{-6} level. Last but not least, we stress once again that the largest FCNC rate both from SUSY-QCD and SUSY-EW is precisely that of the lightest CP-even state $(t \to c\,h^0)$, which is the only Higgs channel that is phase-space available across the whole MSSM parameter space.

2.4 Two-body decays into R-odd particles

In principle there exist three possible two-body decays of the top quark into R-odd particles: $t \to \tilde{b}\chi^+$, $t \to \tilde{t}\tilde{g}$ and $t \to \tilde{t}\chi^0$. These decays were reviewed in [35]. From the latest combined analysis of the four LEP experiments a lower bound on the squark and chargino masses between 80 GeV and 90 GeV is obtained [36]. The exact bound depends on the assumptions of the analysis. The chargino channel is then highly disfavoured, and might be already closed at the end of the present LEP run. The light gluino window ($m_{\tilde{g}} \lesssim 5$ GeV) still exists, but its importance is everyday more marginal [37]. Otherwise the direct limits from the Tevatron $m_{\tilde{g}} \gtrsim 200$ GeV [38] apply, and the gluino decay channel is completely ruled out. So we are left with the neutralino decay channel as the most interesting decay. Note that light top-squarks are a natural feature in the MSSM due to the large top quark Yukawa coupling, and the presence of large mixing in the stop sector. A light top-squark (with small $\tan\beta$) also leads to an enhancement of R_b, pushing